SPECIFICATION

TITLE OF THE INVENTION

VARIABLE OPTICAL ATTENUATOR

Background of the Invention

(1) Field of the Invention

The present invention relates to a variable optical attenuator, and more particularly, to a variable optical attenuator capable of changing output optical power by means of varying the magnitude of optical coupling existing between input and output optical fibers through control of the polarizing state of light.

(2) Description of the Related Art

In association with an increase in the traffic over the Internet, the need to increase the capacity of optical communication has recently become urgent. One of the measures for increasing the capacity of optical communication is to increase a bit rate, and another measure is to employ wavelength division multiplexing (WDM). Prompt realization of an optical device which constitutes such a system is desired.

Here, WDM transmission is a technique for transmitting a plurality of wavelengths over a single optical transmission line (e.g., an optical fiber), wherein data are transferred at respective wavelengths, to thereby increase the capacity of communication. However, when data are transmitted through the optical fiber, propagation loss differs from one wavelength to another, and after transmission over a long distance changes

arise in optical levels of the respective wavelengths.

When a branch device or an erbium-doped fiber (EDF) amplifier is used in the optical transmission line, this phenomenon becomes more noticeable. For this reason, optical levels at respective wavelengths must be made constant before optical transmission is performed. A solution for this is a technique (called "pre-emphasis") for controlling an optical output achieved at the time of transmission beforehand such that an optical level achieved after transmission becomes constant, through use of a variable optical attenuator (hereinafter also called an "optical attenuator"), or the like, which controls levels of individual wavelengths. However, under the assumption that WDM transmission would be performed, optical levels must be set for respective wavelengths (channels). Hence, there must be provided an optical attenuator capable of varying optical power on a per-channel basis.

However, under present circumstance, there are many cases where optical attenuators are provided on a per-channel basis, thereby rendering devices, such as optical repeaters, bulky and incurring a cost hike. A technique described in Patent Publication 1 has hitherto been proposed as a measure for making the device compact. Specifically, as shown in Figs. 16A and 16B, development has been pursued to constitute, as a single device, an optical attenuator capable of varying individual optical power levels of a plurality of channels through use of an optical waveguide device of planar type (or a planar lightwave circuit: PLC) 100. Fig. 16A is a top view of the optical attenuator, and

Fig. 16B is a side view of the optical attenuator.

In the optical attenuator shown in Figs. 16A and 16B, tape fibers (each being formed into a tape by stranding a plurality of optical fibers) 200 are connected to mutually-opposing input and output sections of the PLC 100 within a package (housing) 400. A desired voltage is applied, by way of electrical terminals 300, to electrodes provided in equal number to channels within the PCL 100, thereby changing the refractive index of a waveguide on a per-channel basis in order to change optical power.

Patent Publication 2 describes a conventional "handwritten input display device" which enables handwritten input and display of an image and a character by means of utilizing a phenomenon of changing a polarizing state of light through control of arrangement of liquid-crystal molecules.

[Patent Publication 1]

JP-A-2000-180803

[Patent Publication 2]

JP-A-63-201815

However, the above-described planar lightwave device 100 usually requires micromachining of a quartz substrate through reactive ion etching (RIE) or like processing, thus incurring costs. Further, sufficient miniaturization of the lightwave device cannot be said to have been achieved, for reasons of a limitation on the micromachining technique.

SUMMARY OF THE INVENTION

The invention has been conceived in view of the problem

and aims at providing a variable optical attenuator which is more compact and less expensive than a conventional variable optical attenuator.

To achieve the object, the variable optical attenuator of the invention is characterized by comprising the following elements.

(1) an input/output optical system to which are connected a plurality of input optical fibers and a plurality of output optical fibers and which has a plurality of input lenses for taking beams having entered by way of the input optical fibers as input beams and a plurality of output lenses for gathering output beams to be coupled to the output optical fibers, to thereby couple the output beams to the output optical fibers;

(2) a birefringent device provided on an output side of the input/output optical system;

(3) a liquid crystal device capable of changing polarizing states of the input beams exiting the birefringent device; and

(4) a reflection device which reflects beams passing through the liquid-crystal device so as to return the beams to the output lens of the input/output optical system by way of the liquid-crystal device and the birefringent device.

Here, the input/output optical system, the birefringent device, the liquid-crystal device, and the reflection device are preferably integrated together.

The input/output optical system preferably comprises a fiber array block, in which a plurality of the input optical fibers are arranged and connected in the form of an array and

a plurality of the output optical fibers are arranged and connected in the form of an array and in the same direction as that in which the input optical fibers are arranged; and a lens array block, in which a plurality of the input lenses are arranged in the form of an array in accordance with the arrangement of the input optical fibers in the input array fiber block and in which a plurality of the output lenses are arranged in the form of an array in accordance with the arrangement of the output optical fibers in the output array fiber block.

The liquid-crystal device may preferably have a plurality of sets, each set comprising liquid crystal and electrodes to be used for applying an electric field to the liquid crystal, for controlling polarizing states of different polarizing components of the input light separated by the birefringent device on a per-polarizing-component basis.

A variable optical attenuator according to another embodiment of the invention has the following devices:

(1) an input optical system to which a plurality of input optical fibers are connected and which has a plurality of input lenses taking beams exiting from the input optical fibers as input beams;

(2) a first birefringent device provided on an output side of the input optical system;

(3) a liquid-crystal device capable of varying polarizing state of input beams exiting the first birefringent device;

(4) a second birefringent device provided on an output side of the liquid-crystal device; and

(5) an output optical system to which a plurality of output optical fibers are connected and which has a plurality of output lenses for gathering output light exiting the second birefringent device and coupling the gathered output light to an output optical fiber.

The variable optical attenuator of the invention yields the following advantages:

(1) Input beams are caused to reciprocally pass through the birefringent device and the liquid-crystal device between a plurality of input optical fibers and a plurality of output optical fibers, both being connected to the input/output optical system, through use of the reflection device. Polarizing states of the respective input beams are controlled by means of the liquid-crystal device. The quantity of light coupled to the output optical fiber can be changed freely for respective input beams; that is, on a per-channel basis. A variable optical attenuator compatible with multiple channels can be realized in the form of a compact and inexpensive variable optical attenuator while suppressing an increase in the size of the attenuator and an increase in the area occupied by the attenuator, which would otherwise be caused if the number of channels were increased.

(2) Here, if the input/output optical system, the birefringent device, the liquid-crystal device, and the reflection device are integrated together, the variable optical attenuator can be made much more compact.

(3) Under the assumption that the respective input optical

fibers and the respective output optical fibers are arranged and connected in the form of an array by means of a fiber array block and that the respective input and output lenses are arranged in the form of an array according to the arrangement of the optical fibers by means of the lens array block, even when the number of channels has been increased, the attenuator can be collectively configured by forming individual devices into an array. Hence, the cost of the optical attenuator array per channel can be significantly reduced as compared with the related-art optical attenuator array, by means of significantly curtailing the number of components.

(4) Further, if a pitch between the input optical fibers and a pitch between the output optical fibers are set so as to become greater than a pitch between the input lenses and a pitch between the output lenses, an improvement in polarization extinction ratio can be expected. Hence, occurrence of interference between channels can be inhibited.

(5) Under the assumption that the reflection device is formed from a coupler film which permits transmission of a portion of the light exiting the liquid-crystal device and that an input light monitor light-receiving unit for receiving the light having passed through the coupler film is provided on the surface of the coupler film. The power of input light can be monitored, and hence there can be realized a compact, inexpensive variable optical attenuator capable of incorporating an optical monitor function that is indispensable as an optical output variable component.

(6) Under the assumption that there is further provided an output light monitor light-receiving unit for receiving the light not coupled to the output optical fiber as a result of a variation in the polarizing state of the liquid-crystal device from among the beams reflected from the reflection device, the quantity of light attenuation can be monitored. Similarly, there can be realized a compact, inexpensive variable optical attenuator capable of incorporating an optical monitor function that is indispensable as an optical output variable component.

(7) Under that assumption that, in order to control the polarizing states of the liquid-crystal device for each beam exiting the input optical fiber or for different respective polarizing components of the input light separated by the birefringent device, the liquid-crystal device is constituted by comprising a plurality of sets, each set consisting of a piece of liquid crystal and electrodes to be used for applying an electric field to the liquid crystal, the polarizing state of the liquid-crystal device can be controlled on a per-channel basis or for respective polarizing components of different channels, the quantity of light attenuation can be controlled more precisely, and hence an improvement in polarization extinction ratio can be expected.

(8) Further, under the assumption that the liquid-crystal device is formed by comprising liquid-crystal molecules and glass plates to be used for sandwiching the liquid-crystal molecules, and the reflection device is formed on the surface of one of the glass plates, the liquid-crystal device and the reflection

device can be integrated together, and hence the variable optical attenuator can be downsized further.

(9) Under the assumption that a prism unit—which reflects a portion of incident light in a direction crossing the direction of an optical axis—is interposed between the fiber array block and the lens array block and that a light-receiving unit for monitoring input and output light which receives the light reflected from the prism unit is provided, the power of input light and/or output light can be monitored. Even in this case, there can be realized a compact, inexpensive variable optical attenuator capable of incorporating an optical monitor function that is indispensable as an optical output variable component.

(10) Further, under the assumption that the light-receiving unit is formed from a photodiode array—in which a plurality of photodiodes, each photodiode having a P electrode on one surface thereof and an N electrode on the other surface thereof, are arranged in an array pattern on a conductive transparent substrate such that the other surfaces come into contact with the transparent substrate—and that a common terminal of the N electrodes of the respective photodiodes are provided on the transparent substrate, there is no necessity for providing an N electrode terminal on a per-N-electrode basis. Hence, the number of wiring units is curtailed, thereby improving efficiency. An attempt can be made to downsize the variable optical attenuator by a great extent.

(11) Under the assumption that the light-receiving unit is formed from a photodiode array, in which a plurality of

photodiodes, each having a P electrode on one surface thereof and an N electrode formed around the P electrodes, are arranged in the form of an array on a transparent substrate, a limitation imposed on the materials which can be used for the transparent substrate are mitigated, thereby broadening the range of choice of materials. Therefore, the variable optical attenuator can be made further inexpensive.

(12) Even when the input optical system and the output optical system are constituted individually without use of a reflection device, the variable optical attenuator enables a free change in the amount of light coupled to the output optical fiber on a per-channel basis. Hence, the variable optical attenuator can be realized less expensively than a conventional variable optical attenuator.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A is a schematic plan view showing the basic configuration of a variable optical attenuator employed as a first embodiment of the invention in conjunction with a lightwave;

Fig. 1B is a schematic side view of the variable optical attenuator shown in Fig. 1A;

Fig. 2 is a schematic perspective view showing the variable optical attenuator shown in Figs. 1A and 1B with portions of the attenuator being made transparent;

Fig. 3 is a schematic diagram for describing the principle on which a liquid-crystal element of the embodiment operates;

Fig. 4 is a schematic diagram for describing the principle

on which a liquid-crystal element of the embodiment operates;

Fig. 5 is a schematic diagram for describing the principle on which a liquid-crystal element of the embodiment operates;

Fig. 6 is a schematic diagram for describing the principle on which a liquid-crystal element of the embodiment operates;

Fig. 7A is a schematic plan view showing the configuration of the principal section of the liquid-crystal element of the embodiment;

Fig. 7B is a side view of the principal section when viewed in the direction A shown in Fig. 7A;

Fig. 8 is a schematic plan view showing the configuration of a variable optical attenuator array for describing a specific example of the variable optical attenuator of the embodiment;

Fig. 9A is a schematic top view showing an example overview of a variable optical attenuator array of the embodiment;

Fig. 9B is a schematic side view showing an example overview of a variable optical attenuator array of the embodiment;

Fig. 10 is a schematic plan view showing a first modification of the variable optical attenuator array of the embodiment;

Fig. 11 is a schematic plan view showing a second modification of the variable optical attenuator array of the embodiment;

Fig. 12 is a schematic side view showing a third modification of the variable optical attenuator array of the embodiment;

Figs. 13A to 13C are views for describing a first configuration of a photodiode (PD) according to any of the embodiments;

Figs. 14A to 14C are views for describing a second configuration of a photodiode (PD) according to any of the embodiments;

Fig. 15 is a schematic plan view showing the basic configuration of a variable optical attenuator employed as a second embodiment of the invention in conjunction with an optical path;

Fig. 16A is a schematic plan view showing the configuration of a variable optical attenuator using a related-art planar lightwave circuit (PLC); and

Fig. 16B is a schematic side view of the variable optical attenuator shown in Fig. 16A.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of the invention will be described hereinbelow by reference to the drawings.

[A] Description of the First Embodiment

(A1) Description of the Basic Configuration

Fig. 1A is a schematic plan view showing the basic configuration of a variable optical attenuator (hereinafter also called an "optical attenuator") according to a first embodiment of the invention, along with a lightwave; Fig. 1B is a schematic side view of the variable optical attenuator shown in Fig. 1A; and Fig. 2 is a schematic perspective view showing the variable optical attenuator shown in Figs. 1A and 1B with portions of the attenuator being made transparent.

As shown in Figs. 1A, 1B, and 2, the optical attenuator

of the embodiment is basically constituted of a fiber array block (a fiber-arrayed precision device) 2, a lens array block (a lens-arrayed precision device) 3, a birefringent crystal 4, a liquid-crystal element (a liquid-crystal device) 5, and a reflection element (reflection device) 6. The fiber array block 2, the lens array block 3, the birefringent crystal 4, the liquid-crystal element 5, and the reflection element 6 are integrally arranged without any space therebetween such that input planes of light and output planes of light remain in contact with each other.

Here, an input light fiber 1a and an output light fiber 1b are connected to the fiber array block (hereinafter also called merely "fiber block") 2 in the same direction (e.g., the direction of the Z axis shown in Fig. 1B). An input lens 3a and an output lens 3b, which are arranged in the direction of the Z axis such that the optical axes of the lenses are aligned with the optical axes of the respective optical fibers 1a, 1b, are provided on the lens array block (hereinafter also called simply a "lens block") 3. A collimator lens or a light-gathering lens, which converts input light into collimated light, can be employed as the input lens 3a and the output lens 3b.

The fiber block 2 is also equipped with an input waveguide (input port) 2a for causing the light originating from the core of the input optical fiber 1a to propagate to and enter the input lens 3a of the lens block 3, and an output waveguide (output port) 2b for causing the light originating from the output lens 3b to propagate to and enter the core of the output optical fiber

1b.

Specifically, the fiber block 2 and the lens block 3 constitute an input/output optical system. In the lens block 3, the input lens 3a performs the function of converging into collimated light the light that has entered by way of the input port 2a. The output lens 3b performs the function of gathering the light reflected from the reflection element 6, which will be described later, and coupling the thus-converged light to the output port 3b. As shown in Fig. 1B, when a gap existing between the input lens 3a and the output lens 3b (i.e., an input/output lens gap) G is taken as 0.25 mm (= 250 μm), the input and output optical fibers 1a, 1b are fixed such that a gap existing between the optical fibers in the direction of the Z axis (i.e., an input/output fiber gap) "g" assumes a value of about 0.3 mm (300 μm).

A rutile plate (another crystal may also be usable) which is cut so as to assume an optical axis at an angle of 45°, for example, is used as the birefringent crystal (birefringent member) 4. As shown in Figs. 1A and 2, if such a rutile plate is used, the light that has entered by way of the input lens 3a will be separated into polarized components (an ordinary beam 41 and an extraordinary beam 42) (in the direction of the Y axis), which are polarized orthogonal to each other, while propagating through the rutile plate in the direction of the X axis. In Fig. 1A, the thickness "d" of the rutile plate (i.e., the thickness of the rutile plate in the direction of the X axis) is set to 2.5 mm such that a distance S between the ordinary beam 41 and

the extraordinary beam 42 (i.e., a distance between points of reflection in the direction of the Y axis on the reflection element 6), which are separated from each other, assumes a value of 0.25 mm (250 μm).

The liquid-crystal element 5 can change polarizing states of the respective beams (beams) exiting the birefringent crystal 4 (i.e., for the normal beam 41 and the extraordinary beam 42, respectively). The liquid-crystal element 5 has a structure in which liquid crystal 53 is sandwiched between two glass plates 51, 52. There is utilized a phenomenon of a beam having passed through the liquid-crystal element 5 being converted from a linearly-polarized beam to an elliptically-polarized beam, by means of application of an arbitrary electric field between the glass plates 51, 52 so as to change the birefringence of the liquid-crystal element 5. If such a phenomenon can be utilized, the liquid-crystal element 5 may be a commonly-used liquid-crystal element of nematic type or a liquid-crystal element of another type (smectic type).

For instance, the structure of the liquid-crystal element 5 of a twisted nematic (TN) type will be described by reference to "Principle of a Liquid-Crystal Display" (see the URL http://www.sharp.co.jp/products/lcd/tech/s2_1.html on the Internet, Sharp Corporation). As schematically shown in Figs. 3 and 4, the liquid-crystal element 5 has a structure in which molecules 53' of the liquid crystal 53 are sandwiched between the glass plates (orientation films) 51, 52 having trenches engraved therein in given directions while orientations of the

trenches of the glass plates are offset from each other by 90°.

By means of such a structure, molecules 53' of the liquid crystal 53 (hereinafter denoted as "liquid-crystal molecules 53') having a loose regularity in the direction of a major axis in a natural state are arranged along the trenches of the respective glass plates 51, 52. Further, the liquid-crystal molecules 53' remaining in contact with the glass plate 51 and the liquid-crystal molecules 53' remaining in contact with the glass plate 52 are twisted from each other by 90° between the glass plates 51, 52.

Light travels along a gap between the liquid-crystal molecules 53'. Hence, when the arrangements of the liquid-crystal molecules 53' are twisted, and the light also travels along a twisted path, as schematically shown in Fig. 5 (i.e., a linearly-polarized beam is converted into an elliptically-polarized beam). As schematically shown in Fig. 6, when a voltage is applied between the glass plates 51, 52, the arrangement of the liquid-crystal molecules 53' is changed (i.e., aligned along the electric field) in accordance with the voltage. Hence, light travels in straight lines (i.e., a linearly-polarized beam travels in unmodified form).

On the basis of the above-described principle, the liquid-crystal element 5 can consecutively change the polarizing state of an input beam in accordance with a voltage (i.e., an electric field) applied from the outside. Here, in order to independently change (control) the polarizing state of the ordinary beam 41 and that of the extraordinary beam 42 on a per-beam basis in the same manner as mentioned previously, the

liquid-crystal element 5 is configured in, e.g., a manner shown in Figs. 7A and 7B.

Fig. 7A is a schematic plan view showing the configuration of the principal section of the liquid-crystal element 5 of the embodiment; and Fig. 7B is a side view of the principal section when viewed in the direction A shown in Fig. 7A. As shown in Figs. 7A and 7B, the liquid-crystal 53 partitioned by sealing material 54 constitutes a set in conjunction with transparent (translucent) electrodes 55a, 55b to be used for applying a voltage (electric field) to the liquid-crystal 53. The set is arranged between the glass plates 51, 52 for the ordinary beam 41 and the extraordinary beam 42 (i.e., for different respective polarization components) independently. For example, an indium-tin oxide (ITO) electrode can be used for the transparent electrodes 55a, 55b.

However, the set consisting of the liquid crystal 53 and the transparent electrodes 55a, 55b is not necessarily provided for the ordinary beam 41 and the extraordinary beam 42, respectively. It may be the case that only sets equal in number to input beams—which are not yet separated from each other (i.e., input ports)—are provided as common sets for the ordinary beam 41 and the extraordinary beam 42. However, providing separate sets for the ordinary beam 41 and the extraordinary beam 42 is preferable, because the quantity of light attenuation can be controlled more precisely. Hence, an improvement in polarization extinction ratio can be expected.

The reflection element 6 reflects the light having passed

through the liquid-crystal element 5, to thereby introduce the light again into the liquid-crystal element 5 and the birefringent crystal 4. In the embodiment, the reflection element is formed as a total reflection film formed on the plane of light exit of the liquid-crystal element 5 (i.e., the back of the glass plate 52). The total reflection film may be a multilayer dielectric film or a metal film (Al, Au or the like). Here, the reflection element 6 may be provided as an individual device on a stage subsequent to the liquid-crystal element 5. As mentioned above, integrating the reflection element 6 with the liquid-crystal element 5 through formation of a reflection film is advantageous for miniaturization of a variable optical attenuator.

The basic operation of the optical attenuator of the embodiment having the foregoing configuration will now be described. First, the light exiting the upper input optical fiber 1a enters the input lens 3a provided in the direction of the optical axis after having passed through the input port 2a, as well as into the birefringent crystal 4 after having been converted into collimated light by the input lens 3a.

The light having entered the birefringent crystal 4 is divided into the ordinary beam 41 and the extraordinary beam 42, and the thus-divided beams enter the liquid-crystal element 5. The liquid-crystal element 5 is provided with the pieces of liquid crystal 53 and the transparent electrodes 55a, 55b, which are provided for the respective beams as mentioned previously. The pieces of liquid crystal 53 and the transparent electrodes

55a, 55b can be controlled independently. Hence, the polarizing state of the ordinary beam 41 and that of the extraordinary beam 42, both beams having entered the liquid-crystal element 5, are independently controlled by the corresponding pieces of liquid crystal 53.

As a result, the light having passed through the liquid-crystal element 5 is converted from, e.g., linearly-polarized light into elliptically-polarized light (i.e., a state in which the linearly-polarized light component is merged with a vertically-polarized light component), by means of birefringence of the liquid crystal 53, and enters the reflection element 6 formed on the back of the liquid-crystal element 5.

The light reflected from the reflection element 6 again enters the liquid-crystal element 5. By means of birefringence of a corresponding piece of liquid crystal 53, a change similar to that mentioned previously arises in the polarizing state of light, and the light enters the birefringent crystal 4. Of the beams having entered the birefringent crystal 4, only a component which is identical in polarizing state with the light having entered the birefringent crystal 4 by way of the input lens 3 is finally coupled with the lower output port 2b by way of the output lens 3b. The light is then output to the output optical fiber 1b. As shown in Fig. 1A, other components (beams) 43, 44 do not return to and are not coupled with the output port 2b.

Therefore, the arrangement of the liquid-crystal molecules 53' is controlled through control of the voltage applied to the

two electrodes 55a, 55b provided for the respective pieces of liquid crystal 53. Thereby, the polarizing state of the light that travels back and forth within the birefringent crystal 4 and passes through the liquid-crystal element 5 is controlled for each beam input to the liquid-crystal element 5. As a result, the quantity of light coupled to the output port 2b (i.e., the output optical fiber 1b) can be changed freely on a per-channel basis. Thus, the optical output power can be changed on a per-channel basis.

(A2) Description of a Specific Example

A variable optical attenuator array will now be described hereinbelow as a specific example of the invention on the premise that the array has the foregoing basic configuration.

Fig. 8 is a schematic top view showing the configuration of a variable optical attenuator array of the embodiment. The variable optical attenuator array shown in Fig. 8 has a structure in which a multicore tape fiber 10 (including 12 cores)—into which a plurality of input optical fibers 1a (twelve input optical fibers in Fig. 8) are aggregated in the form of a tape—is connected to an upper layer section of the fiber block 2 as an input tape fiber.

Although not shown in Fig. 8, an analogous multicore tape fiber (including twelve cores) is connected to a lower layer section of the fiber block 2 as an output tape fiber. Specifically, in the present embodiment, the tape fibers are fixed to the fiber block 2 so as to be stacked on top of each other in two layers in a vertical direction (i.e., a direction identical with the

direction of the Z axis shown in Fig. 2) with desired accuracy. An epoxy-based optical adhesive or the like, for instance, is used for fixing the multicore tape fibers (hereinafter also called simply "tape fibers").

The input ports 2a—which are equal in number with the cores of the tape fiber 10 (i.e., twelve input ports)—are arranged into an array within an X-Y plane of the upper layer section of the fiber block 2 at an interval between fiber cores of the input tape fiber 10 (e.g., a pitch of 250 μm). Similarly, the twelve output ports 2b are arranged into an array within the X-Y plane of the lower layer section at the pitch between the fiber cores.

Twelve input lenses 3a are arranged within the X-Y plane of an upper layer section of the lens block 3 so as to coincide with the optical axes of the respective input ports 2a. Twelve output lenses 3b are arranged within the X-Y plane of a lower layer section of the lens block 3 so as to coincide with the optical axes of the respective output ports 2b.

Specifically, a total of 24 (2x12) ports are arranged into an array within a Y-Z plane in the fiber block 2. Similarly, a total of 24 (2x12) lenses are arranged into an array within the Y-Z plane in the lens block 3 in agreement with the arrangement of the ports in the fiber block 2 (i.e., the arrangement of the input and output optical fibers 1a, 1b).

The thickness "d" of the birefringent crystal 4 is set to 1 mm such that a distance S between the ordinary beam 41 and the extraordinary beam 42 assumes a value of about 0.1 mm (100

μm).

As mentioned previously by reference to Figs. 7A and 7B, the set consisting of the liquid crystal 53 and the transparent electrodes 55a, 55b, the liquid crystal being partitioned by the sealing material 54, is provided in the liquid-crystal element 5 for the respective ordinary and extraordinary beams 41, 42 of the light having entered by way of the respective input ports 2a (i.e., a total of 24 sets).

Even in this case, the only requirement for the liquid-crystal element 5 is to use a single glass plate 51 (or 52). The glass plate 52 can be readily formed into an array by means of forming electrodes in one glass plate 52, each electrode having a width corresponding to the size of a beam (about 200 μm). The set consisting of the liquid crystal 53 and the transparent electrodes 55a, 55b may be provided for each input port so as to be common to the ordinary beam 41 and the extraordinary beam 42.

As mentioned above, the variable optical attenuator array compatible with multiple channels (12 channels) can be implemented in the form of a compact, inexpensive variable optical attenuator array while inhibiting an increase in the size of the array and the area occupied by the same, which would otherwise be caused by an increase in the number of channels. Even when the number of channels has been increased, the attenuator can be collectively configured by forming individual members into an array. Hence, the price of the optical attenuator array per channel can be significantly reduced when compared with the

related-art optical attenuator array.

In particular, the variable optical attenuator is formed as a single piece by arranging the fiber block 2, the lens block 3, the birefringent crystal 4, the liquid-crystal element 5, and the reflection element 6 without any space therebetween. When compared with a related-art attenuator using, e.g., a Faraday rotary, the optical attenuator of the invention can be miniaturized significantly.

Figs. 9A and 9B show an example overview of a product of a variable optical attenuator array of the embodiment. Fig. 9A is a schematic top view showing an example overview of a product of a variable optical attenuator array of the embodiment, and Fig. 9B is a schematic side view showing an overview of the same product. As shown in Figs. 9A and 9B, the variable optical attenuator array is constituted by the fiber block 2, the lens block 3, the birefringent crystal 4, the liquid-crystal element 5, and the reflection element 6, which are housed in a premolded package (housing) 11 (having a length of about 18 mm, a width of about 8 mm, and a thickness of about 5 mm) made of resin such as polyphenylenesulfide resin (PPS) or epoxy resin (alternatively, the housing may be made of metal). In Figs. 9A and 9B, reference numeral 12 designates an electrical terminal, and a desired voltage is applied to the transparent electrodes 55a, 55b of the liquid-crystal element 5 by way of the electrical terminal 12.

If an optical system equivalent to that mentioned above can be achieved, reducing the gap between the lenses in the

direction of the Y axis so as to become smaller than 250 μm presents no problem. As a matter of course, fixing of the tape fiber is not limited solely to use of an adhesive. In lieu of separate tape fibers being used for input and output purposes respectively, a commonly available fiber having 2x12 cores can be used for constituting the input/output optical system.

(A3) Description of a First Modification

Fig. 10 is a schematic plan view showing a first modification of the previously-described variable optical attenuator array. In contrast with the variable optical attenuator shown in Fig. 8, in the variable optical attenuator shown in Fig. 10 the thickness of the birefringent crystal 4 (i.e., the length of the crystal in the direction of the X axis) is set to about 2.5 mm such that the distance S between the ordinary beam 41 and the extraordinary beam 42, having been divided by the reflection element 6, assumes a value of about 250 μm, and the pitch between the input ports 2a is set (to about 750 μm) so as to become greater than the pitch between the input lenses 3a (about 250 μm). Therefore, in the variable optical attenuator shown in Fig. 10, the number of input optical fibers 1a and the number of input ports 2a (i.e., the number of channels) are set to "4."

Although omitted from Fig. 10, the input optical fibers 1a and the output optical fibers 1b equal in number to the input ports 2a are arranged at a lower layer section of the fiber block 2 at the same pitch as that existing between the input optical fibers 1a and that existing between the input ports 2a, and the output lenses 3b equal in number to the input lenses 3a are provided

in a lower layer section of the lens block 3 at the same pitch as that existing between the input lenses 3a.

As mentioned above, the pitch between the input optical fibers 1a and that existing between the output optical fibers 1b are set so as to become greater than the pitch existing between the input lenses 3a and that existing between the output lenses 3b. As a result, a large polarization extinction ratio can be ensured, thereby inhibiting occurrence of interference between adjacent ports (i.e., inter-channel interference).

Therefore, in this case, the liquid-crystal element 5 is given such a size (e.g., 0.5 mm in the direction of the Y axis and 2.5 mm in the direction of Z axis) that all ports can be covered with one set consisting of a piece of liquid crystal 53 and the transparent electrodes 55a, 55b. The degree of light attenuation in all channels (ports) can also be collectively controlled. Needless to say, it is better to provide the set consisting of the liquid crystal 53 and the transparent electrodes 55a, 55b for controlling channels (for each of the ordinary beam 41 and the extraordinary beam 42) separately, which arrangement can be expected to yield a great improvement in control accuracy and polarization extinction ratio.

Even in this embodiment, an optical fiber array (an integrated optical fiber) may be used for the input optical fibers 1a (output optical fibers 1b) and the input lenses 3a (output lenses 3b).

(A4) Description of a Second Modification

Next, Fig. 11 is a schematic plan view showing a second

modification of the previously-described variable optical attenuator array. The variable optical attenuator shown in Fig. 11 is identical with that described by reference to Fig. 10. A difference between the variable optical attenuator of this embodiment and that shown in Fig. 10 lies in that the reflection element 6 is constituted not as a total reflection film but as a coupler film 6a for enabling passage of a portion of the incident light; that photodiodes (PD) 61 for monitoring light are arranged in an array in the direction of the Y axis at a position rearward of the coupler film 6a; and that PD blocks 30, each consisting of two light monitor PDs 31, 32, are provided on the surface of the lens block 3 opposing the fiber block 2 such that the PD blocks 30 are provided on both sides of each input port 2a.

The PDs (light-receiving sections) 61 situated rearward of the coupler film 6a are provided at least at positions where the beam exiting the liquid-crystal element 5 (or the ordinary beam 41 and the extraordinary beam 42 separated by the birefringent crystal 4) arrives at the coupler film 6a. Each of the PDs 61 can monitor the quantity of input light (i.e., the power of input light). The PDs 61 may be arranged individually as discrete components. However, in terms of a reduction in the number of components and a reduction in the number of man-hours for manufacturing, use of a PD device array—in which PDs are integrally arranged in an array in agreement with a pitch between the arrival positions—is preferable.

The pair of PDs (light-receiving sections) 31, 32 situated in front of the lens block 3 are provided for receiving beams

which do not return to (or are not coupled to) the output port 2b from among the beams reflected from the coupler film 6a. Here, for example, the PD 31 is arranged so as to receive reflected light (output light) of the extraordinary beam 42 which is not coupled with the output port 2b. The remaining PD 32 is arranged so as to receive reflected light (output light) of the ordinary beam 41, which is not coupled to the output port 2b. Detailed configurations of the PDs 31, 32, and 62 will be described later.

Operation of the variable optical attenuator array having the foregoing configuration will now be described. The light exiting the input optical fiber 1a enters a corresponding input lens 3a by way of a corresponding input port 2a. The light is then converted into collimated light by means of the input lens 3a, and the thus-converted light enters the birefringent crystal 4. The birefringent crystal 4 separates the input light into the ordinary beam 41 and the extraordinary beam 42. The beams pass through the liquid-crystal element 5 and enter the coupler film 6a.

The beams having passed through the coupler film 6a (i.e., the ordinary beam 41 and the extraordinary beam 42) enter the PDs 61. A PD current for the ordinary beam 41 and a PD current for the extraordinary beam 42 are output. On the assumption that a PD current value pertaining to the ordinary beam 41 is taken as PD1 and a PD current value pertaining to the extraordinary beam 42 is taken as PD2, the sum of the two PD current values (i.e., the sum of light-receiving sensitivities = PD1 + PD2) corresponds to the power of input light.

Of the beams reflected from the coupler film 6a, a beam having the same polarizing component as that of the incident light is coupled to the output port 2b by way of the birefringent crystal 4 in the manner mentioned previously. The beam that enters the birefringent crystal 4 as a result of polarizing components of the beam having been changed by the liquid-crystal element 5 is divided into an ordinary beam and an extraordinary beam as in the case of the beam traveling forward in the birefringent crystal. As a result, there arise a beam returning to the output port 2b and beams 43, 44 which undergo birefringence, to thus travel beside both sides of the output ports 2b (i.e., positions separated from both sides of the output port 2b by 250 μm), and do not return to the output port 2b.

The beams 43, 44 are received by the PDs 31, 32, respectively. Here, provided that the PD current value of an ordinary beam is taken as PD3 and the PD current value of an extraordinary beam is taken as PD4, the sum of PD3 and PD4 (i.e., a PD output value) corresponds to the quantity of light which has not coupled with the output port 2b. Therefore, a value determined by subtracting the PD output value (i.e., the sum of PD3 and PD4) pertaining to the output light from the PD output value (i.e., the sum of PD1 and PD2) pertaining to the input light corresponds to the quantity of light attenuation.

By means of calculation of the PD output values, the power of input light and that of output light can be monitored. There can be realized a compact, inexpensive variable optical attenuator capable of incorporating an optical monitor function

that is indispensable as an optical output variable component.

Use of a PD of back incidence type—which enables direct adhesion of the coupler film 6a and the lens array block 3 (or the birefringent crystal 4) as structures of the PDs 31, 32, and 61—is preferable. As a matter of course, a commonly-employed PD of front incidence type can also be used. However, in this case, a required space must be provided between the coupler film 6a and the light incidence surface of PDs, in view of convenience of wiring. For instance, an epoxy-based optical adhesive is preferable for fixing PDs.

A preferable light-receiving diameter of the PDs 31, 32, and 61 is, e.g., 300 μm, regardless of the types of PDs employed. In the case of a PD of front incidence type, a PD having a smaller light-receiving diameter can also be applied to the PDs by means of reducing the diameter of a beam through arrangement of lenses in the space.

(A5) Description of a Third Modification

Fig. 12 is a schematic side view showing a third modification of the previously-described variable optical attenuator array. The variable optical attenuator shown in Fig. 12 is identical with that shown in Fig. 10. A difference between the variable optical attenuator of this embodiment and that shown in Fig. 10 lies in that a prism (coupler film prism) 13 formed from sandwiched coupler films 13a, 13b is provided between the fiber block 2 and the lens block 3 such that input light and output light can be extracted in a direction orthogonal to the direction of the optical axis (i.e., the direction of the X axis); that

PDs (input monitor PDs: light-receiving sections) 14a are provided on the upper surface of the prism 13 at positions corresponding to the respective input ports 2a; and that PDs (output monitor PDs: light-receiving sections) 14b are provided on a lower surface of the prism 13 at positions corresponding to the respective output ports 2b.

Here, the coupler films 13a, 13b have characteristics such that the film reflects a portion of incident light (e.g., 5% of incident light) in a direction orthogonal to the direction of the optical axis and that the film allows passage of the remaining portion (95%) through the coupler films in unmodified form. Consequently, the coupler film 13a reflects 5% of the light having entered by way of the input port 2a, to thereby cause the light to enter the PDs 14a, and allows passage of the remaining 95% of the light, to thereby cause the light to enter corresponding input lenses 3a of the lens block 3.

The coupler film 13b reflects 5% of the light exiting the output lens 3b of the lens block 3, to thereby cause the light to enter the PD 14b and allows passage of the remaining 95% of the light, to thereby cause the remaining light to enter corresponding output ports 2b. The thickness of the prism 13 (i.e., the length of the prism 13 in the direction of the X axis) is set to a value of, e.g., 500 μm. The transmission factor (a reflection factor) of the coupler films 13a, 13b can be changed, as required.

As a result, even the variable optical attenuator of the embodiment can also monitor the power of input light and the

power of output light on a per-channel basis by means of the PDs 14a, 14b. Hence, the optical monitor function that is indispensable for a variable optical output component can be incorporated into the optical attenuator while an attempt is made to attain miniaturization and cost cutting.

The PDs 14a, 14b are also preferably formed by causing PDs of back incidence types to adhere directly to the surface of the coupler film prism 13. Use of an epoxy-based adhesive for fixing the PDs is preferable. As a matter of course, even in this case, a commonly-employed PD of front incidence type can also be used. In terms of convenience of wiring, there cannot be adopted a configuration in which the PDs are caused to adhere directly on the surface of the prism 13. Hence, a required space must be provided.

A preferable light-receiving diameter of the PDs 14a, 14b is, e.g., 300 μm, regardless of the types of PDs employed. In the case of a PD of front incidence type, a PD having a smaller light-receiving diameter can also be applied to the PDs by means of reducing the diameter of a beam through arrangement of lenses in the space. The PDs 14a (14b) may be provided on the prism 13 discretely. However, in terms of a reduction in the number of components and a reduction in the number of man-hours for manufacturing, use of a PD device array—in which PDs are integrally arranged in an array in agreement with a pitch between the input ports 2a (or output ports 2b)—is advantageous.

The previously-described embodiment adopts a pair consisting of the coupler film 13a and the input monitor PD 14a

and another pair consisting of the coupler film 13b and the output monitor PD 14b so that input and output light can be extracted and monitored respectively. As a matter of course, it may be the case that only one of the pairs is adopted.

(A6) Connection Pattern of PDs

The configuration of the previously-described PD 61 and those of the PDs 31, 32, 14a, and 14b will be described in detail hereinbelow. For the sake of convenience of description, these PDs are not distinguished from each other and are denoted as PDs 20.

(A6.1) First configuration example of PD 20

Figs. 13A, 13B, and 13C are views for describing the first configuration example of the PD 20. Fig. 13A is a side view; Fig. 13B is a top view; and Fig. 13C is a view of the PD when observed through the back of Fig. 13B.

The respective PDs 20 shown in Figs. 13A, 13B, and 13C are of back incidence type. In each of the PDs 20, a P electrode 22 is provided on one surface, and an N electrode 23 is provided on the other surface (light-receiving surface). The surface of the PD 20 provided with the N electrode 23 is taken as a mount surface, and the PDs 20 are arranged and fixed on the conductive transparent substrate 21, such as a transparent electrode, in the form of an array. P electrode terminals 24 are connected to the respective P electrodes 22, and a common terminal (N electrode common terminal) 25 is connected to the respective N electrodes 23 on the transparent substrate 21.

Adoption of such a structure obviates a necessity for

providing N electrode terminals for the respective N electrodes 23, thereby curtailing the number of wires and achieving improved efficiency. Thus, an attempt can be made to pursue a more compact and lower-cost variable optical attenuator.

(A6.2) Second configuration example of PD 20

Figs. 14A, 14B, and 14C are views for describing the second configuration example of the PD 20. Fig. 14A is a side view; Fig. 14B is a top view; and Fig. 14C is a view of the PD when observed through the back of Fig. 14B. The respective PDs 20 shown in Figs. 14A, 14B, and 14C are also of back incidence type. In this case, the PD 20 has the following structure. Namely, one surface (light incidence surface) of the PD 20 is taken as a mount surface, and the PDs 20 are arranged on a transparent substrate 21' in the form of an array. The P electrode 22 connected to the P electrode terminal 24 and the N electrode terminal 26 provided around the P electrode terminal are provided on the other surface.

Here, the transparent substrate 21' may possess conductivity as in the case of the previously-described transparent substrate 20 or may be of non-conductive type. In this case, a limitation imposed on materials which can be used for the transparent substrate 21' is mitigated as compared with the first configuration example, thereby broadening the range of choice of materials. Therefore, an attempt can be made to curtail costs of the variable optical attenuator to a great extent through selection of material.

When such PDs 20 are provided, it is desirable to house

the PDs 20 in the premolded package 11 (see Figs. 9A and 9B) while sealing portions of the variable optical attenuator with resin so as to cover wire portions of the terminals 24 (or 25) and 26.

[B] Description of Second Embodiment

Although in the first embodiment the variable optical attenuator of reflection type is configured through use of the reflection element 6, the variable optical attenuator can also be configured without use of the reflection element 6 in the same manner as in the first embodiment.

For instance, as shown in Fig. 15, a fiber (array) block (fiber-arrayed precision device) 2A, a lens (array) block (lens-arrayed precision device) 3A, and a birefringent crystal 4A are provided on an input side of the liquid-crystal element 5; and a fiber (array) block (fiber-arrayed precision device) 2B, a lens (array) block (lens-arrayed precision device) 3B, and a birefringent crystal 4B are provided on an output side of the liquid-crystal element 5 such that the fiber blocks, the lens blocks, and the birefringent crystals become symmetrical about the center of the liquid-crystal element 5. Even in such a case, the fiber blocks 2A, 2B, the lens blocks 3A, 3B, the birefringent crystals 4A, 4B, and the liquid-crystal element 5 are arranged in an integrated fashion without a space therebetween while light input surfaces or light output surfaces respectively remain in contact with each other.

Even in this embodiment, the input-side fiber block 2A is provided with input ports 2a which are provided for each input

optical fiber 1a to be connected and cause the light exiting the input port 1a to propagate through the lens block 3A. Input lenses 3a arranged in agreement with the arrangement of the input ports 2a (in more detail, so as to coincide with optical axes of input light exiting the input ports 2a) are provided in the input-side lens block 3A.

The input-side birefringent crystal 4A and the output-side birefringent crystal 4B (i.e., the first and second refractive devices) are identical with or analogous to the birefringent crystal 4 of the first embodiment. The liquid-crystal element 5 is also identical with or analogous to that described in connection with the first embodiment.

Output lenses 3b arranged so as to coincide with optical axes of the input lenses 3a are provided in the output-side lens block 3B. Output ports 2b—which are arranged so as to coincide with optical axes of the input lenses 3a and cause the light exiting corresponding output lenses 3b to propagate to the output optical fibers 1b—are provided in the output-side fiber block 2B.

The configuration of this embodiment corresponds to a configuration in which the fiber block 2, the lens block 3, and the birefringent crystal 4, which are used in the input/output optical system in the first embodiment for both forward and backward directions, are provided separately for the input optical system (i.e., the fiber block 2A, the lens block 3A, and the birefringent crystal 4A) and the output optical system (i.e., the fiber block 2B, the lens block 3B, and the birefringent

crystal 4B).

Fig. 15 shows only the pair of fibers 1a, 1b, the pair of ports 2a, 2b, and the pair of input lenses 3a, 3b. As a matter of course, those pairs are provided in equal number to required channels as in the case of, e.g., the embodiments shown in Figs. 8 and 10.

Operation of the optical attenuator of the embodiment having the foregoing configuration will now be described. The light exiting the input optical fiber 1a enters the input lens 3a provided in the axial direction by way of the input port 2a. The light is then converted into collimated light by means of the input lens 3a, and the thus-converted light enters the input-side birefringent crystal 4A.

The light having entered the birefringent crystal 4A is divided into the ordinary beam 41 and the extraordinary beam 42, and the thus-divided beams enter the liquid-crystal element 5. Even in this embodiment, the liquid-crystal element 5 is equipped with the liquid crystal 53 and the transparent electrodes 55a, 55b for each beam, to thereby enable independent control of the beams. Hence, the polarizing state of the ordinary beam 41 and that of the extraordinary beam 42, both beams having entered the liquid crystal element 5, are individually controlled by the liquid crystal 53. Subsequently, the beams enter the output-side birefringent crystal 4B.

Of the beams having entered the birefringent crystal 4B, only the light components whose polarizing states coincide with the polarizing state of the light having entered the birefringent

crystal 4A by way of the input lens 3 (i.e., forward-traveling light) are finally coupled to the output port 2b by way of the output lenses 3b and output to the output optical fibers 1b.

Therefore, even in this case, the quantity of light coupled to the output port 2b (output optical fibers 1b) can be freely changed on a per-channel basis by means of control of a voltage applied to the liquid-crystal element 5. Hence, the output power of light can be changed on a per-channel basis, and the variable optical attenuator can be realized at lower cost than can the conventional variable optical attenuator.

Even in this case, the fiber blocks 2A, 2B; the lens blocks 3A, 3B; the birefringent crystals 4A, 4B; and the liquid-crystal element 5 are arranged in an integrated fashion without a space therebetween while light input surfaces or light output surfaces remain in contact with each other. Hence, when compared with a related-art attenuator using, e.g., a Faraday rotary, the optical attenuator of the invention can be downsized significantly.

Even in this embodiment, there is no necessity for separate provision of the set consisting of the liquid crystal 53 and the transparent electrodes 55a, 55b for the ordinary beam 41 and the set for the extraordinary beam 42. The sets may be provided in equal number to input beams before separation (i.e., the number of input ports) so as to be shared between the ordinary beam 41 and the extraordinary beam 42. When a polarization extinction ratio is improved by increasing the pitch between the ports, one set consisting of the liquid crystal 53 and the transparent

electrodes 55a, 55b may cover the entire port.

As in the case of the embodiment described by reference to Fig. 12, a prism having a coupler film (i.e., a coupler film prism) may be provided so as to extract input and output beams in a direction orthogonal to the direction of the optical axis (i.e., the direction of the X axis), and monitor PDs for receiving the thus-extracted beams may also be provided. By means of such a configuration, even this embodiment enables monitoring of power of input and/or output light, and hence a light monitor function indispensable for a light output variation component can be incorporated into the optical attenuator.

Needless to say, the invention is not limited to the foregoing embodiments and can be implemented while being modified in various manners within the scope of the invention.